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Application of Optical Fibre Sensors to Measuring the Mechanical Properties of Composite Materials and Structures

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1. Introduction

The role of polymer composites in mechanical structures has been steadily increasing. The key factor here is the coefficient of specific strength, i.e. a ratio of tensile strength to specific gravity. As compared with metals, this coefficient assumes a high value for composites, including the polymer ones. Other major factors determining the choice of materials are: the product price, mass manufacturability, high strength and durability, corrosion resistance, material production and machining energy consumption and a few more. Also the latter criteria increasingly favour composites. Materials engineering as applied to composites offers the possibility of creating entirely new materials and modifying the traditional materials, which in both cases better meet designers' expectations.

The ever increasing popularity of composite structures is first of all due to the considerable reduction in weight in comparison with metal structures, at a sufficiently high mechanical durability. Nevertheless, the safety requirements require that the stress-strain state of composite structure be monitored. Standard NDE methods such as radiography, interferometric holography, ultrasonic scanning or visual inspection are usually not effective in on-line monitoring. Even if they were used for periodic checks, they would not be able to detect promptly defects critical to the condition of the monitored structure. Moreover, conventional measurement devices, such as electrical resistance strain gauges, often get damaged in adverse environmental conditions.

State-of-the-art measuring methods based on optical fibre technology are increasingly often used to monitor the structural health of industrial objects. Optical fibre sensors have many advantages over the conventional devices. The obvious one is that they can work at high levels of electromagnetic interference and in other adverse conditions (high dust concentration, high temperature, high pressure, significant deformations). Moreover, such sensors are characterized by high (deformation and temperature) measuring sensitivity in a wide measuring range. Owing to their small geometric dimensions and a relatively small weight they can be installed inside a structure (e.g. by embedding them in the composite material) or on its surface. Thanks to their high potential for multiplexing it is possible to create a nervous system of the object being monitored, enabling health and damage assessment. In addition, optical fibre based sensors ensure spark-proof safety which is an important consideration for inflammable applications.

Because of the wide range of problems connected with the measurement of mechanical quantities in composites by means of optical fibre sensors it becomes necessary to concentrate on major problems. The authors decided to focus on the structural health monitoring (SHM) aspects for all kinds of composite structures. Solutions being mainly the result of the authors' own research, with reference to the literature on the subject, will be highlighted.

Considering the above, the objective is to present the fundamentals of the measurement method based on optical fibre sensors as applied to:

- monitoring the behaviour of, among others, laminates and pultruded composites used as reinforcement in building structures and aeronautical structures;
- measuring (static and cyclic) strains in Smart composites where strong magnetic fields limit or exclude the use of other measuring techniques;
- monitoring the structural health of composite structures subjected to extreme strain, such as composite pressure vessels for storing compressed hydrogen and methane car fuels.

The focus is on the experimental aspect of measurements, and the numerical modelling of composite materials and structures is deliberately neglected. However, one should note that modelling plays an important role in many measurement situations (e.g. it is used to determine the number and location of sensors, the theoretical state of strain on a meso- and macroscale, the distribution of temperature, etc.).

2. Composite materials and importance of SHM

Currently most of the research and applications are concerned with composites whose matrix is made of polymers, ceramic materials or metals (e.g. aluminium, titanium, nickel and other alloys) and which are reinforced with glass or carbon fibres. Such composites have found wide application in the manufacturing of fuselages and other structural components of planes, gliders, space shuttles and rockets, car body components, fuel tanks, yacht hulls and masts, wind turbine blades and domestic appliances components, in medicine and in many other fields. Moreover, composites are used to reinforce the existing building structures, including the historic ones (e.g. to preserve bridges, churches, etc., or to increase their load-bearing capacity).

The percentage of composite materials used in high-tech applications increases every year, causing a rise in the production of reinforcing fibres. It is estimated that the demand for carbon fibres in 2018 will increase by about 275% (from 41240 to 113500 tons) as compared with that in 2010, (Sloan, 2010). The highest increase in demand is forecasted for applications connected with the wind power industry (700%), the storage of compressed fuels (~410%) and the broadly understood aerospace industry (~220%).

The interest in composite materials is due to their very good mechanical (strength) parameters and low specific gravity. Highly valuable is the possibility of creating a composite with strictly defined parameters for a given structure. Moreover, increasingly often various (mainly optical fibre based) sensors are incorporated into the structure of composite materials. Thanks to this, different parameters (e.g. strain and temperature) can be measured directly in the structure's material. Another major advantage of optical fibre sensors (OFS) is that they can be used to detect defects and their accumulations and to determine the safe life of the material during its service. In recent years most of the research

on OFS has been devoted to their use for the continuous monitoring of the structural health of composite elements.
Novel structural health monitoring (SHM) systems for composite structures are currently developed. Thanks to the use of measuring systems integrated with the structure the latter can be optimally managed. Continuous monitoring enables the detection of hazards in the structure, undetected by inspections or modelling. Consequently, the damaged components can be promptly replaced whereby the safe service life can be extended. Moreover, thanks to SHM systems the knowledge about structures and their behaviour in real conditions can be improved whereby the next generation of such structures will be better designed. Ultimately, the costs connected with building new structures will be lower and the safety, reliability and life of the latter will increase (Glisic & Inaudi, 2007).

3. Optical fibre sensors and measuring technique fundamentals

Currently optical fibre sensors (OFS) are increasingly widely used to monitor the mechanical properties of composite materials and structures in their operating conditions where the reliability and safety of the structures (often working under extreme strains) is critical. Typical applications of various OFS to condition monitoring are presented below. Strain (displacement) and temperature are the main parameters which can be measured by such techniques. On the basis of the measured strain and temperature one can estimate other mechanical parameters, such as stress/strain distribution, force, pressure, curvature, leakage and so on.

3.1 Fibre bragg gratings

Fibre Bragg gratings (FBG) are the most popular fibre based sensors. A Bragg grating is a structure made inside the core of a single-mode optical fibre, characterized by periodical changes in the value of the refractive index (Fig. 1). Due to the presence of such a modulated

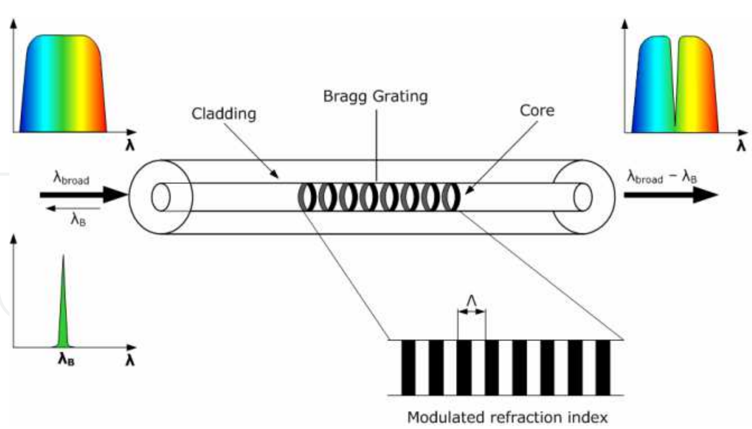


Fig. 1. Scheme of fibre Bragg grating principle of operation

structure inside the core of the optical fibre some of the optical radiation transmitted through the latter is reflected from the grating structure while the remainder is propagated without any loss (Yu & Yin, 2002). The wavelength reflected from the Bragg grating, the so-called Bragg wave (λ_B), is described by the relation:

$$\lambda_B = 2 \cdot n_{eff} \cdot \Lambda \qquad (1)$$

where: n_{eff} – the effective refractive index of the optical fibre core, Λ – a Bragg grating constant.
Sensors bonded to the external surface of the monitored structure or located inside the material are subject to deformations causing changes in the Bragg wavelength, which becomes the touchstone for the measured deformations. It should be noted, however, that a change in λ_B in real measuring systems is the result of the simultaneous influence of temperature and deformations, which can be measured in ranges: -270°C ÷ 800°C and -3% ÷ 3%, respectively.

3.2 Interferometric SOFO® sensors

Another type of OFS applicable to composite structures are interferometric sensors (i.e. SOFO® sensors with long measuring arms). Interferometric optical fibre sensors are characterized by the modulation of the light signal phase propagated in the measuring system (Glisic & Inaudi, 2007). The measuring heads of SOFO® sensors, in the form of a single-mode optical fibre, may attain from a few centimetres to a dozen or so meters and are either integrated with the surface of the monitored object (e.g. by means of special tape – SMARTape®) or located inside the monitored structure (e.g. in the case of tested vessels they are buried in the composite). The sensors are designed to measure displacements (deformations). The measurement consists in analyzing the difference in the phases of the optical signals propagating in the two arms (the measuring arm and the reference arm) of the Michelson interferometer (Fig. 2).

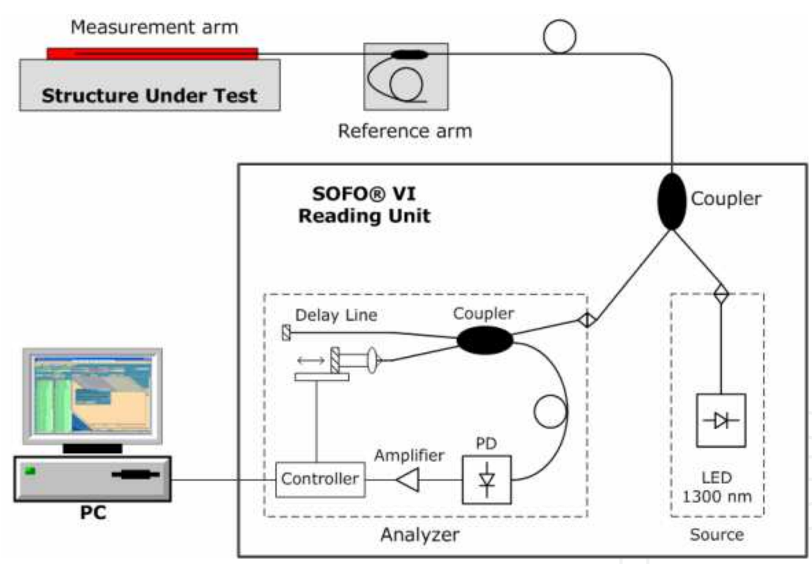


Fig. 2. Scheme of Smartec SOFO® interferometric measuring system (Glisic & Inaudi, 2007)

The measuring arm is in direct contact with the examined structure. The reference arm is separated mechanically from the monitored object, but it is still close enough for the temperature of both arms to be the same. Thanks to this the influence of temperature fluctuations on the measurement results is eliminated. The change in the phase of the light wave is a result of the change in the length of the optical fibre constituting the measuring head. Because of the interference of the two beams it is possible – through an analysis of interference fringes – to quantitatively determine the deformation of the sensors and consequently, the deformation of the monitored structure (Glisic & Inaudi, 2007). Since interferometric sensors belong to a group of sensors with long measuring arms (long-gage sensors), the measured deformations are averages for the whole length of the sensor.

3.3 EFPI sensors

Extrinsic Fabry-Perot interferometric (EFPI) sensors are built from two optical fibres facing each other, but with a small air gap (in the order of micrometers) between them, inside a capillary. The working principle of EFPI sensors is based on multi-reflection Fabry-Perot interference between optical signals reflected from air-glass interface mirrors (Leng & Asundi, 2003). The scheme of the EFPI principle of operation is shown in Fig. 3.

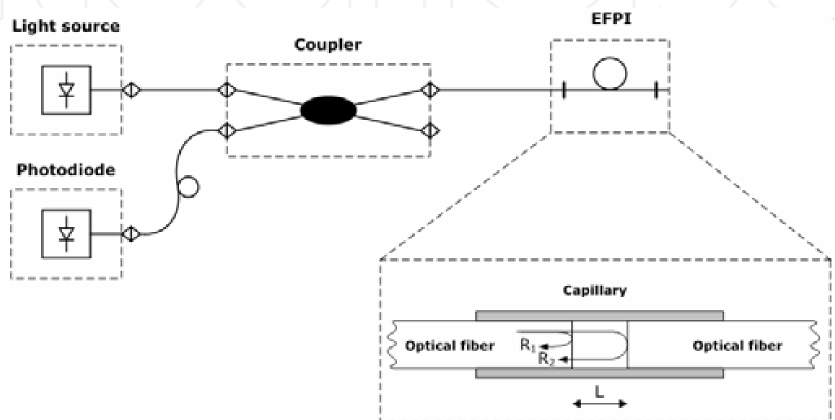


Fig. 3. Scheme of system based on extrinsic Fabry-Perot interferometric sensors

Changes in air gap length (L), which in fact are changes in sensor length, correspond to the variation in the applied mechanical strain. They can be measured by demodulating the interference signal, i.e. by means of coherent or low-coherent techniques (Glisic & Inaudi, 2007).

4. Selected applications of OFS to composite elements

There is a great variety of fibre-optic measuring methods which are used in the monitoring of composite structures. Therefore in the literature survey the authors decided to focus on the areas in which they have considerable achievements and experience. Among others, the monitoring of laminates and pultruded composites, structural aircraft components, SMART magnetic composites and composite pressure vessels for storing CH2 and CNG is discussed.

4.1 Reinforcing laminates and pultruded composites

Optical fibre sensors have found the widest application in the measurement of deformations of all kinds of laminates and pultruded composites. This is owing to several advantages which OFS have, such as:

- similar material properties of the sensor and the reinforcing material in the composite,
- OFS, even the ones complicated in shape, can be located directly in the material (sensor small size and weight and measuring head flexibility),
- resistance to electromagnetic interference (the sensor is a dielectric),
- a wide range of measured physical quantities and simultaneous measurement in many points,
- resistance to environmental conditions.

OFS, usually in the form of bare-fibre Bragg gratings or interferometric sensors, are located directly between the successive layers of the laminate or are interwoven with reinforcement bundles in the case of woven/drawn elements. Depending on the method of manufacturing the composite and its end use, the sensor may be impregnated with resin during the production of the material ("wet" methods such as pultrusion and winding) or later using the vacuum method.

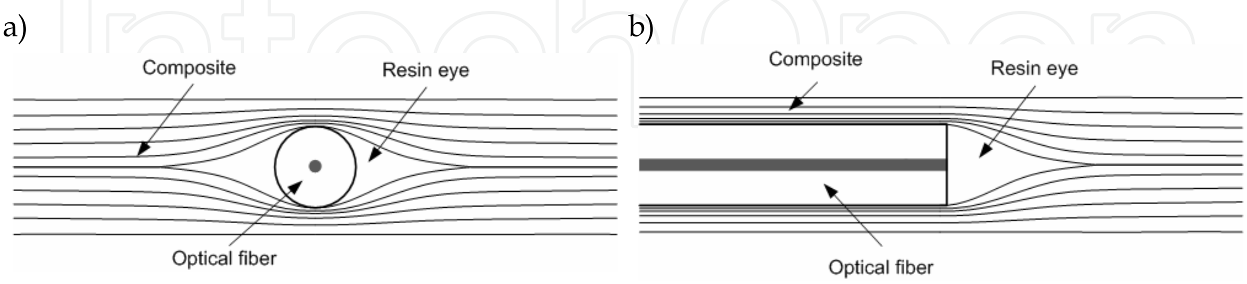


Fig. 4. Scheme showing how local defects arise in composite laminates with embedded optical fibre sensors (Balageas et al., 2006)

Nevertheless, one should also note potentially negative aspects which need to be taken into account or eliminated (or their effect minimized). One of the drawbacks is the sensor size. Even though the optical fibre diameter is relatively small (typically 125 μm), it is quite considerable in comparison with that of the fibres used to reinforce the composite (amounting to ~16 μm for glass fibres and ~8 μm for carbon fibres) and with the thickness of a single laminate layer. Thus by locating the optical fibre inside the composite one may introduce areas of reinforcement discontinuity (Lee et al., 1995). These areas are excessively filled with resin and are referred to as resin pockets or resin eyes (Fig. 4). The disturbances n stress field distribution in the material may initiate delamination of the latter (Balageas et al., 2006; Udd et al., 2005).

The size and shape of a local defect in the form a resin pocket depend on the orientation of the optical fibre relative to the reinforcement fibres. The laminate's mechanical parameters are least affected when the sensor is laid along the direction of the reinforcement and most affected when it is laid perpendicularly to the latter. If the sensor is laid parallel to the reinforcing fibres and the two ends of the optical fibre are led outside the area of the sample, the size of the additional defect in the laminate is close to zero (Balageas et al., 2000).

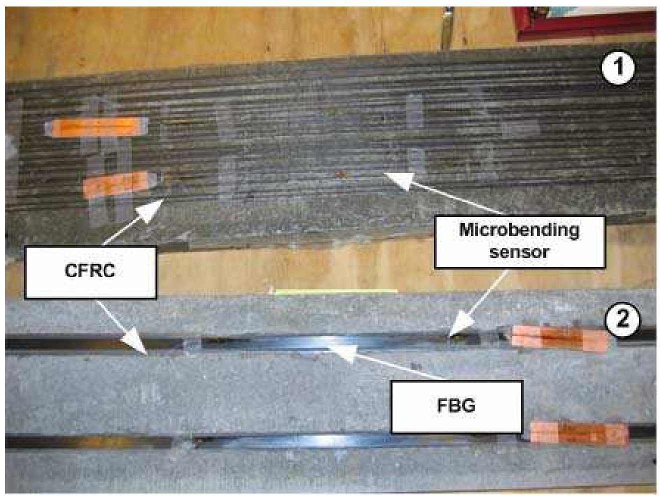
Another aspect which needs to be considered is the effect of the process of manufacture of composite laminate on the measuring properties of the FBG sensors located inside it. In (Kuang et al., 2001) the authors analyzed the spectrum reflected from the fibre Bragg grating in the reference environment (outside the composite before installation), comparing it with the response of a sensor embedded directly between the layers of the laminate. For some test samples they found the spectrum reflected from the sensor to be distorted and widened. This was due to the locally strong nonuniformity of the load acting on the sensor along its whole length (7 mm). Such local nonuniformities in the distribution of the strain field resulted mainly in an increase or decrease of the Bragg grating constant (Λ), which manifested itself in the splitting of the single Bragg wave peak into several peaks. This behaviour of the sensor was observed mainly for laminates consisting of several composite layers laid at different angles relative to each other. In the case of unidirectional composites, only a shift of the reflection (Bragg wave) spectrum towards lower values, due to the local compression or tension of the sensor as a result of the manufacturing process (e.g. resin curing in elevated pressure and temperature conditions), was observed. The possibility of fibre-optic monitoring of resin curing during the manufacture of high-strength laminates was described by, among others, Leng in (Leng & Asundi, 2003). Thanks to the use of FBG and EFPI sensors residual strains during curing can be determined and local material defects in the form of delaminations can be detected. The quoted authors prepared samples made up of 16 layers of carbon prepregs, between which optical fibre sensors were installed along the direction in which the reinforcement had been laid. In addition, a Teflon disk 300 mm in diameter was placed in one of the samples to simulate a local delamination. In order to harden them the samples were annealed at a temperature of up to 120°C. By analyzing the signals received from the sensors installed in the samples with and without the defect one could detect the local damage already during the curing process. It was also found that residual strains after the curing of the samples are greater along the direction of compression for the flawed sample. The difference between the signals received from the EFPI and FBG sensors for the samples during curing amounted to 5-10% (Leng & Asundi, 2003). Then in order to determine their bending strength the samples were subjected to the three-point bending test. The test results confirmed that the strength of the samples with the designed flaw was lower than that of the samples without the flaw and that the artificially introduced delamination reduced the stiffness of the structure (Leng & Asundi, 2003).

One of the main uses of laminates and pultruded composites is the reinforcement of the existing structures or structures under construction. The strength and load-bearing capacity of such structures as bridges, viaducts and buildings are commonly increased by introducing (through bonding) additional reinforcement made of materials characterized by high tensile strength and stiffness (e.g. laminates or pultruded composites in the form of strip or mat) glued to the surface of the structure being reinforced. Thanks to its relatively little weight the reinforcement does not additionally weight down the structure.

But composite reinforcements have drawbacks – they tend to creep and are brittle. For this reason research is underway aimed at the detection and control of internal material defects at the early stage in their development (Majumder et al., 2008). For example, a method of manufacturing glass fibre reinforced composites (GFRC) and carbon fibre reinforced composites (CFRC) through pultrusion with FBG and EFPI sensors located inside is presented in (Kalamkarov et al., 1999). The quasi-static and cyclic test measurement results received from the optical fibre sensors for the tested samples were in agreement with the results obtained from extensometric measurements. Moreover, it was shown that optical fibres with polymer cladding are characterized by better parameters of the sensor/material bond. Sensors in acrylic cladding tended to separate from the laminate and could not be used in composites which required manufacturing processes conducted at a temperature of above 85°C. In the case of the sensors in the polymer cladding the allowable temperatures were as high as 385°C (Kalamkarov et al., 1999).

The use FBG sensors located in pultruded epoxy-glass (GFRP-OFBG) and epoxy-carbon CFRP-OFBG) composites designed for reinforcing concrete beams is described in (Zhou et al., 2003). The composite elements prepared in this way were cast in concrete, cured and subjected to three-point bending. The FBG sensors registered the strains of the composite rods in a range of up to 200 microstrains (with an accuracy of 1÷2 $\mu\varepsilon$), registered the cracking of the concrete layer and informed about the slipping out of the reinforcements from the concrete. The authors showed that pultruded composite rods (with incorporated sensors) can be used both as elements increasing the load-bearing capacity of a structure (reinforcing the latter) and as measuring heads integrated directly with the monitored element.

a)



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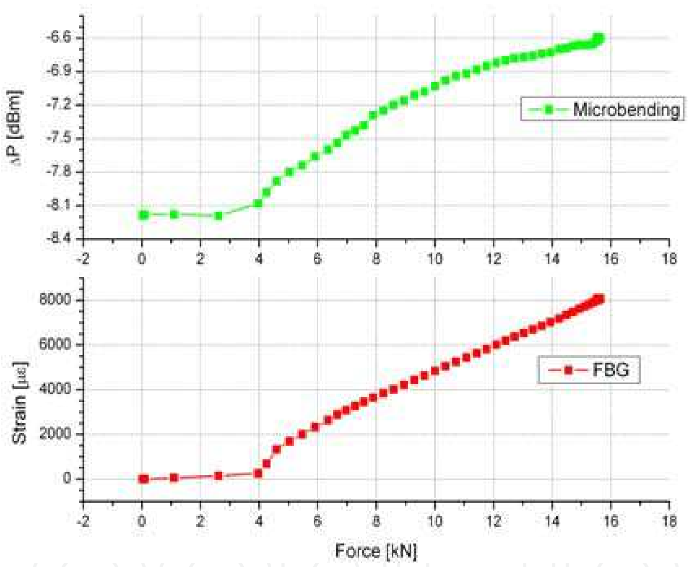
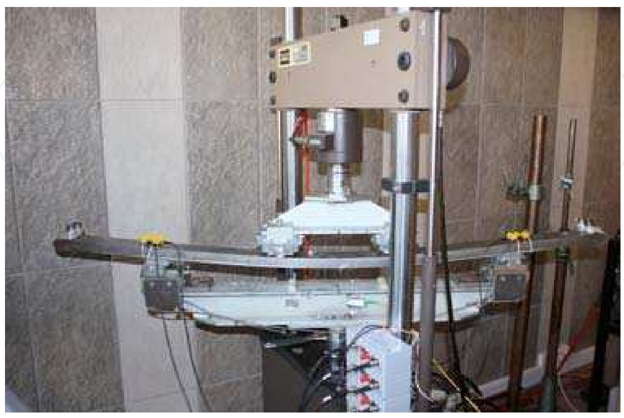


Fig. 5. Tested beams with composite reinforcements: (a) laboratory made in IMSAM (1) and by Polish Bridges company (2), and (b) characteristics registered by respectively microbending sensor and FBG sensor for beam with commercial composite reinforcement (Błażejewski et al., 2007)

Above one can find exemplary results of investigations into the monitoring of composite reinforcements of engineering structures, carried out by the present authors. Composite reinforcements, in the form of pultruded CFRC and GFRC strips, were glued to the tested concrete beams. Besides the reinforcements, two types of optical fibre sensors, i.e. FBG sensors and amplitude microbending measuring heads, were employed. Figure 5a shows two tested concrete beams with composite reinforcements (made in the laboratory in the Institute of Materials Science and Applied Mechanics (IMSAM) at Wrocław University of Technology and by the Polish Bridges (PB) company) and embedded optical fibre sensors.

During three-point bending in an MTS810 strength tester the following were registered as a function of time: the force, the strain (measured by the FBG sensors) and the change in optical power (registered by the microbending head).

a)



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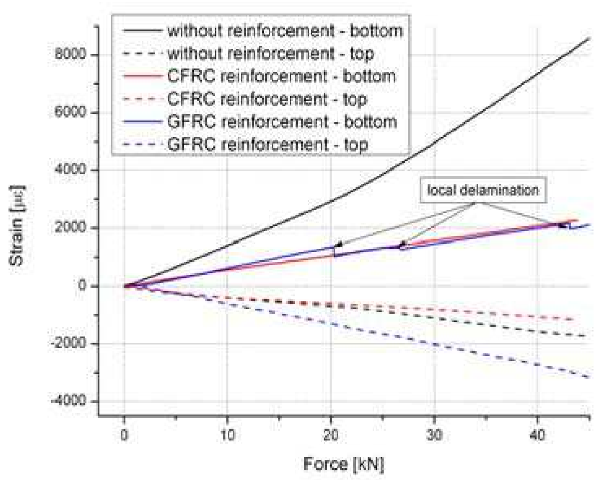


Fig. 6. Four-point bending of steel beam reinforced with unidirectional carbon-epoxy composite with integrated FBG sensors (a) and comparison of measurement results for different reinforcements (b)

Figure 5b shows exemplary measurement results for the microbending sensor and the FBG sensor, as a function of the force applied to the tested concrete beam with the Polish Bridges reinforcements. Similar measurements were carried out for concrete beams without reinforcement and with the laboratory made glass composite and carbon composite reinforcements. On this basis the effect of the type of reinforcement on the strength of the concrete beams was determined. The tests confirmed the suitability of optical fibre sensors for the testing of engineering structures reinforced with elements made of composite materials (Błażejewski et al., 2007).
Then tests were carried out for two types of reinforcement (pultruded carbon/glass reinforcement) with integrated FBG sensors, designed to increase the load-bearing capacity of steel frame structures. The reinforcement together with the sensor was glued to the

beam's (tensioned) bottom. An additional reference (FBG) sensor was installed on the top (compressed) side. The reinforced beams were subjected to the static four-point bending test during which the force and the strain in two areas were registered.

The measurement results are presented in Fig. 6b. An additional measurement was performed on a steel beam without any reinforcements to determine the effect of the composite of the structure. It was found that the reinforcements applied made the beam stiffer whereby its load-bearing capacity increased as manifested by lower strains in comparison the beam without reinforcements under the same static load. Thanks to the reinforcement the elastic range of the whole beam increased (up to about 20 kN). In the strain-force diagram for the beam with glass reinforcement one can see local jumps in the registered strain values (at ~20.2 kN, 26.4 kN and 43 kN), indicating that the reinforcement locally gets unstuck from the structure. In the sample, this manifested itself in local whitening of the composite.

4.2 Aerospace structural components

Owing to their excellent mechanical properties, particularly high strength and stiffness, composite components are increasingly used in aerospace structures. Modern planes (e.g. Boeing B787) include many subassemblies made from composite materials, especially carbon fibre reinforced composites (CFRC). Their (volumetric) percentage in the total aircraft parts is as high as 80%, which amounts to 50% of the ready aircraft weight. However, the development of defects in composite materials is much more complicated than in metallic materials and it is still not fully explored (Diamanti et al., 2002). For this reason, in recent years much research has been devoted to structural health monitoring (SHM), also of aerospace structural components, by means of fibre-optic measuring techniques. The research projects are aimed at developing systems for monitoring aerospace structures not only during their everyday operation, but also during the processes of production (e.g. pressure and vacuum forming, resin impregnation and curing, machining, assembly, etc.) of the particular composite components.

In (Takahashi et al., 2010) the authors describe a method of developing a system for the continuous monitoring of the composite parts of the plane's fuselage (a partition with reinforcements) through a system controlling the state (distribution) of strain on its surface during the entire production stage and service life. The developed system was based on Bragg gratings integrated with the structure of a CFRC reinforced composite. Through the measurement of local strains the system can detect and locate defects and other damage arising in the structure's material. The authors also showed that it was possible to measure the strain of composite samples in the course of the whole process of pressure forming and described its effect on the tested object. In order to determine the optimum location of point FBG sensors on the reinforced composite partition a numerical FE model was created and loaded on its outer surface with a pressure corresponding to the maximum design pressure.

Two types of defects: reinforcement separation and local impact into the partition resulting in the delamination of the composite were implemented in the virtual model. Thanks to this it became possible to determine the optimum distance between FBG sensors, ensuring detection of defects in any area of the investigated object. It was estimated that the intersensor distance for sensors with a sensitivity of 10 $\mu\varepsilon$, installed on the reinforcements should not exceed 100 mm. In the case of the sensors controlling the surface of the partition, one FBG grating is capable of detecting a defect within an area 300 mm in diameter.

A major problem which designers of systems for continuous structural health monitoring encounter is the location of measuring transducers and their optimization with regard to the number of measuring points. The constraints put on the number of sensors are aimed at reducing the measuring system costs (e.g. costs of sensors, instrumentation, measuring units, system installation). They are also dictated by difficulties with the on-line processing of large quantities of measurement information. A large number of sensors does not always guarantee system reliability. Proper software with implemented data processing algorithms, capable of keeping the user informed about potential risks, is also needed.

Besides research on optimizing the arrangement and number of sensors (e.g. through numerical modelling and the hybrid (model + experiment) approach), purely experimental research on implementing the very wide networks of sensors (comprising a few thousand and more sensors) is being conducted. The aim is to create SHM systems which, similarly as the human nervous system (nerves/sensors, the brain/the information processing unit), enable the monitoring of entire engineering structures (Balageas et al., 2001).

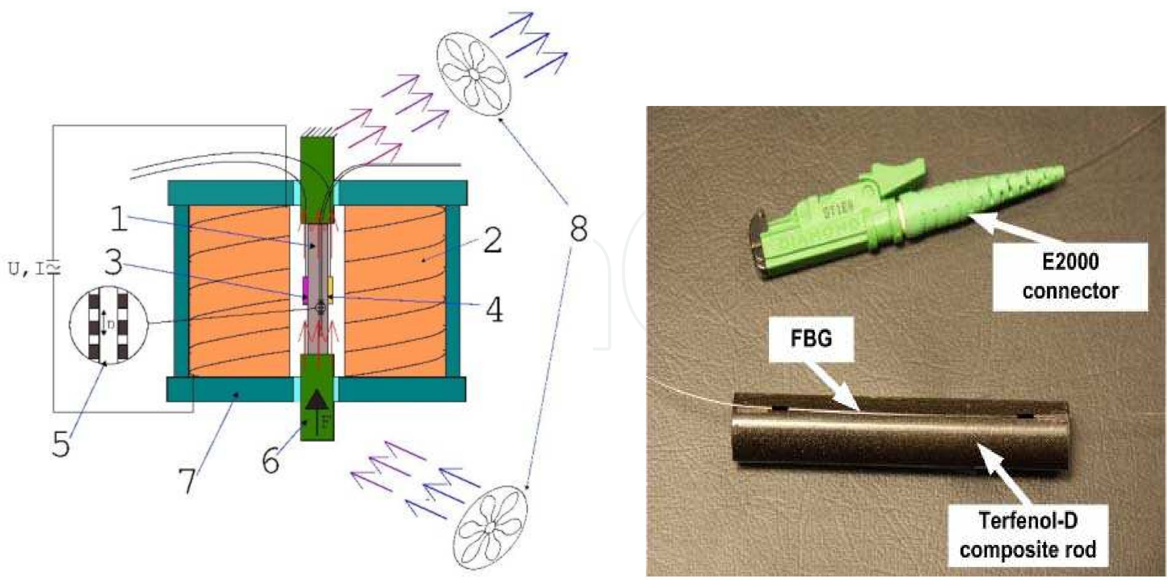
Exemplary research on implementing an SHM system comprising a large number of sensors is presented in the paper (Childers et al., 2001). The authors describe a measuring system consisting of 3000 measuring points based on fibre Bragg gratings, for monitoring the strain of a transport plane wing. Static tests on 12 m long composite wing made of carbon-epoxy composite with Kevlar inserts were carried out. A system consisting of 466 foil strain gauges was used as the reference. A novel system for handling many FBG sensors in a single fibre had been specially designed for the tests. The system is based on the optical frequency domain technique (OFDR) and is capable of simultaneously reading signals from 4 measuring heads. Each of the heads is 8 m long and contains 800 sensors spaced at every 10 mm.

The results obtained from the two different measuring systems were very similar. Moreover, it was found that thanks to the use of the fibre-optic system the total weight of the measuring system could be considerably reduced and at the same the number of measuring points could be increased. As a result, the behaviour of the structure under real loads could be more accurately represented. In addition, owing to the small number of cables the system based on Bragg gratings turned out to be much easier to install than the strain gauge system (Childers et al., 2001).

4.3 SMART magnetic composite elements

SMART magnetic materials (SMM) are active materials which in recent years have been increasingly often and wider used in the aerospace industry, the navy, the car industry, civil engineering and in many other fields (Schwartz, 2002). The so-called giant magnetostrictive materials (GMMs) form a major subgroup in SMM. They enable the conversion of magnetic energy into mechanical energy and vice versa with high efficiency. A typical representative of GMMs is Terfenol-D which offers many advantages but its low tensile strength and the occurrence of high eddy currents detract from them. Attempts are made to eliminate the drawbacks by creating composites. For several years now research projects, e.g. (Kaleta et al., 2009; Gąsior et al., 2009; Yin Lo et al., 2006), targeted at creating magnetostrictive materials capable of assuming the form of, e.g., rods or laminates and effectively replacing solid Terfenol-D, have been conducted. Such composites offer the possibility of new applications, in e.g. SHM (tagging).

a)



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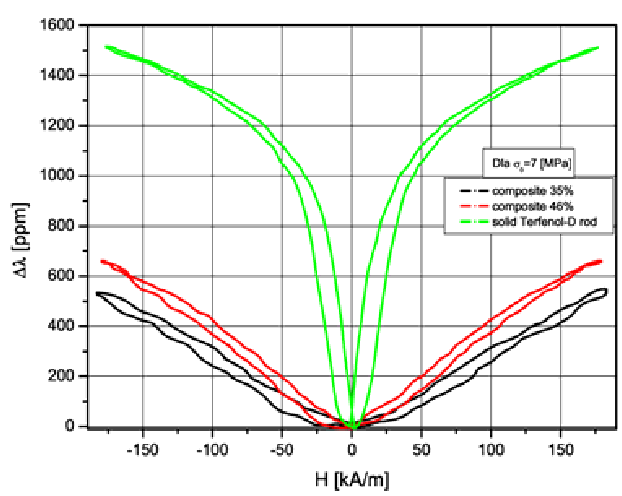


Fig. 7. Composite sample containing powdered Terfenol-D, with installed fibre-optic sensor and test stand for magnetostrictive composites (a) and exemplary change in longitudinal magnetostriction under influence of applied magnetic field for different composite and solid samples, registered by FBG sensor (b) (Kaleta et al., 2009)

Monolithic (solid) GMMs and composites incorporating them are tested mainly with regard to their magnetic properties. The parameters describing these properties are magnetostriction (the deformation of a ferromagnetic under the influence of an external magnetic field) or the opposite effect (the Villary effect). In both cases, the conventional methods of measuring strains (e.g. by means of extensometers or strain gauges) are practically inapplicable since GMMs are inside coils (or even constitute their core) and the sharp fluctuations in E-M fields there disturb the measurement.

For this reason, optical fibre sensors are an ideal solution for measuring the mechanical parameters of magnetic materials (including GMMs). Owing to their dielectric nature they are resistant to all electromagnetic interferences and in addition, enable strain registration with an accuracy as high as 1 με.

In (Kaleta et al., 2009; Gąsior et al., 2009) the authors used FBG sensors to measure the deformation of solid Terfenol-D rods and composite rods based on epoxy resin and powdered Terfenol-D. The fibre-optic sensors were installed on the surface of the samples (Fig. 7a) in the longitudinal and circumferential directions whereby magnetostriction could be measured in two directions. During the bonding of the sensors to the samples the latter were prestressed. As a result, strains could be measured under both compression and tension. This is important since in order to obtain optimum operating conditions for these composites they need to be prestressed (Kaleta et al., 2009).
The aim of the static tests described in the above papers was to determine the magneto-mechanical properties of rods made of GMM composites and solid Terfenol-D. Their magnetostriction was determined depending on the percentage of the magnetic phase in the material (Fig. 7b). The test results showed that although the magnetostriction is three times lower in comparison with that of the solid material, it is about 30 times higher than that of nickel (the reference material). But the influence of eddy currents was eliminated and the tensile strength increased (Kaleta et al., 2009).

4.4 Composite pressure vessels

Today composite pressure vessels are used in many fields, such as: the car industry, the aerospace industry, rescue services, etc. They owe their popularity to the considerable reduction in the weight of the vessel in comparison with steel vessels, and to their high mechanical strength. Also their excellent resistance to corrosion is not without significance. In order to illustrate the subject, a case of a composite hydrogen vessels is presented below. The use of hydrogen to feed fuel cells and for combustion in conventional engines requires a safe and expensive fuelling method. Storing hydrogen in pressure vessels of the CH2 (compressed hydrogen) type has become the predominant technology, especially in cars. The latest (4th generation) designs are pressure vessels with a nominal working pressure (NWP) of 70 MPa. The weight of the vessel itself should be low enough in order for the latter to be installed in a car without the necessity to reduce the boot space. For this reason, wholly composite vessels (Fig. 8) must be installed. The load-bearing wrapping of such a vessel is made from high-strength carbon fibres (CFRC) while the liner (ensuring tightness) is made of high-quality plastics. The burst test pressure (BTP) at a safety factor of 2.35 (for CFRC) has to be above 164.5 MPa. In the case of glass composites (GFRC) the safety factor increases to 3.65 whereby BTP is higher.

a)

b)

Fig. 8. Examples of pressure vessels for storing CNG and CH2: of type 2 (a) and type 4 (b), (Błażejewski et al., 2007)

Because of the stringent requirements the CH2 vessel is an integrated high-tech product which can withstand extreme strains, and all its building components, i.e. the materials, the calculations, the design, the lining and wrapping technologies and the test methods, represent the cutting edge of research and engineering. The problem of SHM for such a vessel is discussed below. The discussion is based on the present authors' experience gained in carrying out research projects, among others, within the 6th EU Framework Program (Storage of Hydrogen – StorHy) and the 7th UE FP (Integrated GAS Powertrain – InGas).

The combination of the highly-strained composite load-bearing structure of the vessel and the hazardous substance (which compressed hydrogen fuel is) necessitates the monitoring of the structural health of such objects. It is estimated that the danger area in the case of explosion of a full car methane tank is 250 m large in diameter and in the case of hydrogen it may be as large as 1000 m in diameter (Mair, 2007). Therefore it is of critical importance to ensure operational safety over the entire ten-year service life.

At the moment the standards require that pressure vessels be subjected to routine tests certifying them fit for further use, but it is not necessary to permanently install SHM systems. Because of such regulations pressure vessel manufacturers prefer to increase the amount of the material reinforcing the structure to increase its safety than to optimize the the vessel design. This leads to higher production costs and a higher final product price. However, currently efforts are made, e.g. (Sulatisky et al., 2010), to exert pressure on the legislative bodies to introduce regulations reducing the current high safety factors for the manufacture of pressure vessels when a continuous structural health monitoring is employed. As already mentioned, standard NDE methods are not suitable for the on-line monitoring of such objects and can be used only for periodic inspections (Foedinger et al., 1999; Degrieck et al., 2001). A system of sensors should ensure the assessment of the technical condition of the high-pressure cylinder during both its production and (above all) its long use.

The research in this field, e.g. (Foedinger et al., 1999; Degrieck et al., 2001; Kang et al., 2006; Hernández-Moreno et al., 2009; Sulatisky et al., 2010; Błażejewski et al., 2010; Glisic & Inaudi, 2004; Frias et al., 2010), shows that the best of the offered solutions is to use optical fibre sensors for this purpose, since they are characterized by resistance to electromagnetic interference, non-sparking safety, ease of integration with the structure of the composite material and high sensitivity in a wide measuring range. Such sensors, permanently installed on the surface of the vessel or incorporated into the structure of the composite material, enable the continuous monitoring of the structure's technical condition over its whole service life.

In one of the first works (Foedinger et al., 1999) dealing with the application of optical fibre sensors to the monitoring of the structural health of standard testing and evaluation bottles (STEBs), the authors used FBG sensors which were integrated with the composite load-bearing layer as it was being wound during its manufacturing. The sensors were to measure the strain and temperature of the vessel during the curing of the epoxy resin and quasi-static pressure tests. A micrographic analysis of the cross sections of the composite load-bearing shell containing the optical fibre was carried out and showed good interaction between the two as well as no defects in the areas incorporating the sensors. The latter were located in several areas of the pressure vessel, e.g. in its cylindrical part and in its bottoms. Each time they were positioned in the direction consistent with the direction of the reinforcement, which means that they were wound at different angles to the principal axis of the vessel. In addition, resistance strain gauges and thermocouples were employed as the reference sensors. The strain gauges were installed on the vessel's outer surface (after resin curing) in the neighbourhood of the fibre Bragg gratings. The investigations showed good agreement between the sensor measurement results and the strain gauge measurement results (depending on the winding direction and the location, the difference between the FBG sensor results and the strain gauge results ranged from 1.2% to 24%) and the numerical FE model results.

In (Degrieck et al., 2001), the authors investigated the possibility of using fibre Bragg gratings to monitor the strains of components made of composite materials, including laminates and pressure vessels made by winding. The research was carried out in several stages. First tensile tests and temperature tests were carried out on a bare optical fibre with an FBG sensor. Then carbon-epoxy laminate with a fibre Bragg grating placed between the layers was made. The laminate was subjected to the static three-point bending test. Finally, a pressure vessel was made by winding a glass fibre, in which an optical fibre together with a Bragg grating was wound (in the circumferential direction) with the final reinforcement layer, parallel to the latter. The vessel was then subjected to tests. In the first test it was statically loaded with an internal pressure of 0-16 bar and then cyclically with 0-3 bar. In both tests a change in pressure resulted in a shift of the Bragg wave reflected from the sensor incorporated into the structure of the composite load-bearing layer. It was found that being located directly in the material structure, FBG sensors are ideal for measuring strains in composite materials and in addition, they represent a promising technique for nondestructive testing and evaluating the structural health of composite elements (Degrieck et al., 2001).

The suitability of optical fibre (FBG) sensors for monitoring composite pressure vessels, especially taking into account the possibility of integrating such sensors with the load-bearing layer during the manufacture of vessels by winding, is the subject of the paper (Kang et al., 2006). The authors describe the difficulties they encountered while embedding measuring heads (made by welding FBG sensor together) in a composite material. Only one of the four measuring heads in a pressure vessel with the sensors prepared in this way survived the manufacturing process (winding and high-temperature curing). It turned out that because of their low resistance to lateral stresses in the weld, the welded fibres are poorly resistant to the conditions prevailing during vessel manufacturing whereby the risk of optical fibre damage during reinforcement winding increases considerably. Measuring heads consisting of several sensors produced directly in one optical fibre segment additionally coated with a thin protective layer proved to be much better. In the latter case, the percentage of sensors which after the vessel manufacturing process were still fit for measurements increased to ~79% (11 out of the 14 sensors were available). By comparing the reflection spectrum for the pressure vessel before annealing with the spectrum for the ready vessel one could determine the local residual strain. In all the measuring points local compression amounting to several hundred microstrains ($\mu\varepsilon$) was registered, but the strains at the vessel bottoms were relatively larger (Kang et al., 2006).

Then the vessel was subjected to the pressure test until failure. For reference purposes, strain gauges were installed on the vessel's surface. The gauges were damaged before the vessel burst. The maximum registered strains amounted to 0.95% for the pressure of 2900 psi (~200 bar). Also the splitting of the Bragg wave into several peaks was observed – probably due to the displacement of a sensor relative to its optimal position fixed during winding (the sensor was not situated parallel to the reinforcement fibres), (Kang et al., 2006).

The reliability and safety of composite vessels with an integrated SHM system is also the subject of the research conducted by Hao and others (Hao et al., 2007). They proposed to create a system which would monitor the circumferential and longitudinal strain of a tested vessel made of glass-epoxy composite, by means of three FBG sensors installed on its surface. In addition the authors used two strain gauges to locally measure strains in the circumferential and longitudinal directions. The tested vessel (with a 3.2 mm thick load-bearing wall) was statically loaded with a pressure of 0-200 bar. The obtained measurement results showed good convergence for the strains registered in the longitudinal direction, particularly in a low pressure range (up to 8 bars), and large scatters for the circumferential strains. The differences between the FBG sensors and the strain gauges amounted to as much as 60%, even though they were separated by a distance of maximum 12 mm. According to the quoted authors this is due to the different distances of the sensors from the defect around which the vessel burst (Hao et al., 2007).

The use of fibre Bragg gratings for the monitoring of the state of stress of a composite pressure vessel was also the subject of research carried out by Frias and others (Frias et al., 2010). In their paper the authors describe a measuring system based on six FBG sensors and two piezoelectric polyvinlyidene fluoride (PVTF) sensors, integrated with the composite vessel structure. The sensors were located between the steel liner and the load-bearing layer made of glass fibre in thermoplastic resin. The liner was made by welding the two bottoms and the circumferential FBG sensors were located in the direct vicinity of the weld. The other sensors (two Bragg gratings and two piezoelectric sensors) were located in the cylindrical part, and registered longitudinal strains. The vessel was subjected to cyclic testing within which 9 test series with 30 cycles in each were carried out. The upper cycling pressure amounted to 5-40 bar with a 5 bar step in the successive series. The test results showed good convergence for the different measuring systems. Moreover, the liner in the weld region was found to plasticize quickly under the cyclic loading, as indicated by the circumferential FBG sensors. The latter showed that the vessel behaved nonlinearly in the circumferential direction in the weld area and linearly in the longitudinal direction outside this area (Frias et al., 2010).

Glisic and his co-workers in (Glisic & Inaudi, 2004) presented the application possibilities of a system for monitoring the structural health of 4th-type composite (the so-called full composite, a polymer liner and carbon-epoxy reinforcement) pressure vessels for storing compressed methane in cars, with a nominal working pressure of 350 bar. The proposed measuring system is based on interferometric SOFO® sensors. The latter are characterized by relatively long measuring arms which average the measured strain over their length. The aim of the research carried out within the EU ZEM Project (the 5th EU Framework Program) was to develop a topology of sensors distribution on a vessel, and a proper algorithm analyzing the measurement data, enabling the detection of local defects which could endanger the safety of the users (Glisic & Inaudi, 2004).

SMARTape® sensors were integrated with the vessel structure and located between the last carbon fibre layer and the first glass fibre layer. The interferometric SOFO® sensors measured strains in the longitudinal direction (four sensors spaced at every 90° on the circumference) and in the circumferential (helical) direction (2 sensors with opposite lead angles).

Glisic and Inaudi proposed an algorithm (a monitoring strategy) for measurement data analysis which made it possible to detect different anomalous behaviours of the vessel and defects arising in its structure. It was assumed that in the case of damage the vessel would

become more deformable (under a constant pressure), which meant that the slope of the strain-pressure line would change. It was also assumed that a local defect could result in local deformations (e.g. ovalization, bending) of the vessel, which would be registered by pairs of SOFO® sensors distributed symmetrically on its surface. Thanks to the latter assumption the correlation of measurements between selected sensors could be analyzed. In the case of a defect, the linear dependence between the strains registered by one sensor and the ones registered by another sensor will be disturbed and will change (Glisic & Inaudi, 2004).
In order to prove the above assumptions a series of static and quasi-static tests were carried out on new pressure vessels and vessels with designed flaws (cuts differing in their geometrical dimensions and delaminations), subjected to a pressure of 0-350 bar. The authors of (Glisic & Inaudi, 2004) show that an increase in such parameters as deformability or the relative compliance coefficient and a change in the reciprocal linear dependence between the particular sensors are indications of vessel damage.

5. Structural health monitoring of composite pressure vessels

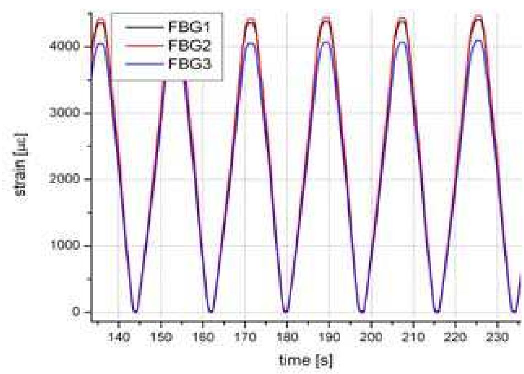
5.1 Concept of composite pressure vessel monitoring system

The on-line monitoring of a pressure vessel is not limited to only the measurement of the mechanical parameters (e.g. strain fields) of its composite load-bearing layer. In order to determine the vessel's structural health and to detect critical defects which may pose a risk to the safety of the users it is necessary to employ proper algorithms to analyze the acquired measurement data. An ideal solution to this problem is a hybrid method in which the acquired measurement data are compared with the numerical model of the monitored object. Moreover, a good numerical model should indicate the primary sensor locations to be taken into account when installing sensors. However, this approach is not always possible, usually due to the lack of sufficient information needed to create a reliable numerical model of the investigated object. In addition, the use of the hybrid method necessitates the use of separate numerical models for each type of vessel. Any change in the design must be properly taken into account in the modelling process.
In the case of pressure vessels for which there is no precise information on the geometry of the load-bearing wrapping or the materials used, the present authors proposed to use a method consisting in analyzing local changes in the strain field (measured in many places) during the service life of the vessel and comparing them for particular pressure values. Any deviations from the assumed uniform strain field distribution in the vessel's cylindrical part indicate its potential damage (Błażejewski et al., 2008).
In order to create a fully functional system of monitoring the structural health of composite pressure vessels a special coefficient called ABS (absolute value) was calculated and compared with the threshold value. The ABS coefficient value was calculated as the absolute value of the difference between the coefficients of the directional strain-pressure lines for the successive vessel stress cycles. In addition, in order to locate possible defects the ABS coefficient values were compared between the particular measuring points (sensors). For a pressure vessel with no defects the dependencies between the particular sensors should be the same or very similar (considering the uniform state of stress in the load-bearing layer). When damage (e.g. a delamination or a crack) arises, the strain field is no longer uniform and the dependencies between the sensors are disturbed (Błażejewski et al., 2010).

5.2 Cyclic tests of pressure vessels

A pressure vessel with a steel liner, for storing hydrogen was subjected to cyclic tests at room temperature in accordance with the Draft ECE Compressed Gaseous Hydrogen Regulation, 2003. The vessel was loaded with pressures in the maximum range of 20-875 bar on a test rig in the Institute of Materials Science and Applied Mechanics at Wrocław University of Technology.

a)



b)

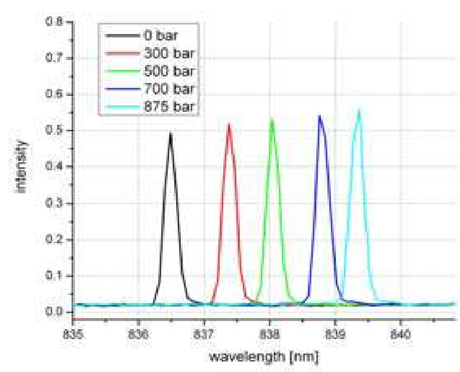


Fig. 9. Hoop strain characteristic registered by fibre Bragg gratings in different places of vessel (a) and Bragg wave shift registered by sensor FBG1 for different internal pressures (b) (Błażejewski et al., 2007)

Optical fibre sensors (FBG) for local strain measurement were used for the monitoring of the structural health of the vessel. In addition, acoustic emission sensors were employed for reference measurement purposes (Błażejewski et al., 2007). In the course of the basic tests (20-875 bar) about 700 cycles simulating vessel operation (filling-emptying) were carried out. The diagram in Fig. 9 shows exemplary vessel hoop strains registered by sensors: FBG1, FBG2 and FBG3 during cycle loading and the variation in the length of the Bragg wave registered by the FBG1 sensor in a pressure range of 0-875 bar. It should be noted that the vessel's circumferential strains for the pressure of 875 bar are relatively high (ranging from ~4000 to 4500 με depending on the type of sensor), (Gąsior et al., 2007).

Figure 10 shows the maximum strains (at internal pressure P_{max}=875 bar) registered by the FBG sensors installed in the circumferential direction, versus the number of vessel loading cycles. It should be noted that an increase in the number of cycles results in a local increase in registered strain values (enlarged fragment A in Fig. 10) leading to the failure of the vessel. This is due to the fatigue (cyclic softening) of the steel from which the liner was made. The bursting of the vessel was preceded by rapid increase in locally registered circumferential strains (enlarged fragment B in Fig. 10). By analyzing the slope of the strain-number of cycles curve in its linear region one can determine how long the vessel can safely remain in service, i.e. predict its life. This is particularly important in the case when pressure vessels are to stay in service for many years.

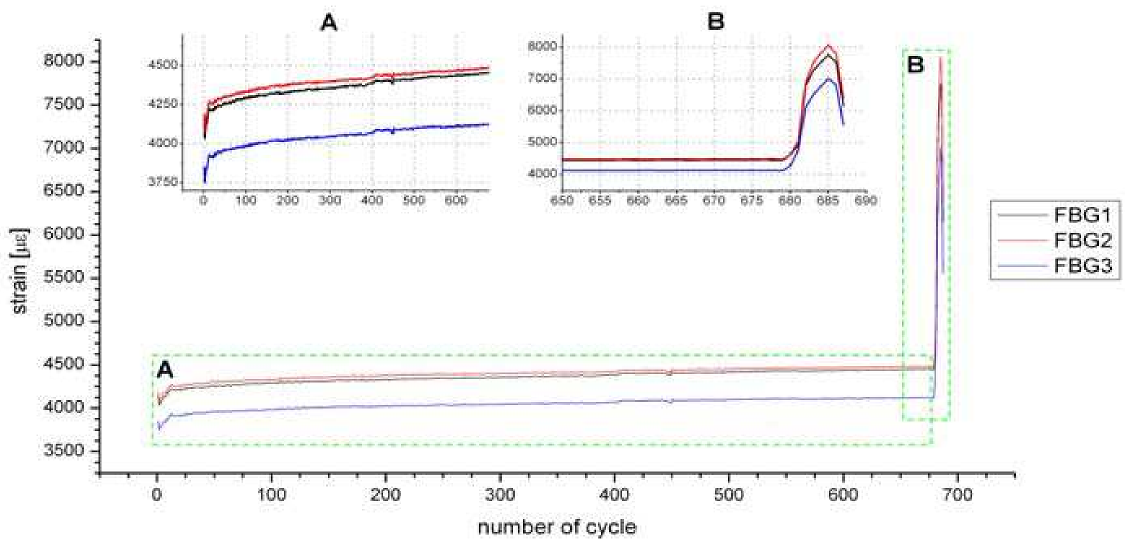


Fig. 10. Maximum circumferential strain (for P = 875 bar) versus number of vessel loading cycles and close-ups of marked areas, (Błażejewski et al., 2007)

Figure 11 shows signals registered by the particular sensors (the circumferential FBG sensors, the strain gauges and the acoustic emission sensors) at the moment of failure of the vessel (the broken line in Fig. 11). It is apparent that the failure was preceded by the previously mentioned rapid increase in strains (in the order of 1500 ÷ 3000 με depending on the sensor and its distance from the defect) registered in the circumferential direction. Moreover, there is good correlation between the measured changes in the strain field on the vessel's outer surface and the acoustic signals registered by the AE sensors. At the moment of failure a considerable increase in the root mean square (RMS) acoustic emission signal occurs, which indicates a high degree of damage to the composite layer (Gąsior et al., 2007).
Figure 12 shows an analysis of local circumferential strains for the last 8 cycles of the tests to which the pressure vessel was subjected. The analysis was carried out in accordance with the procedure described in sect. 5.2, consisting in the determination of the ABS coefficient. Its value was calculated as the difference between the directional coefficients for the strain-pressure lines obtained from the reference measurement and the next measurements. The first of the measurements was adopted as the reference point. Figure 12 shows a marked jump in ABS coefficient values between cycles 3 and 4 for all the analyzed measuring points. Moreover, the differences between the particular ABS coefficient values increase, which is a symptom of nonuniformity of the strain field distribution on the external surface of the vessel. This situation is indicative of the strong development of defects in the load-bearing structure of the composite pressure vessel (Błażejewski et al., 2008).

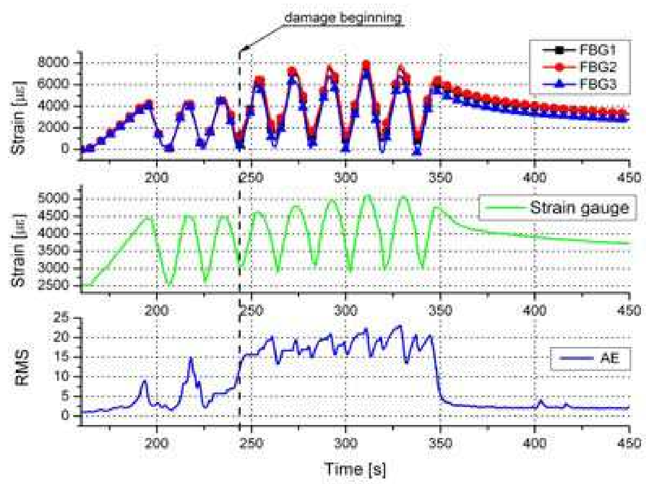


Fig. 11. Local circumferential vessel strains registered by FBG sensors (upper diagram) and strain gauges (middle diagram), and acoustic emission signal (bottom diagram) at instant of vessel failure (Gąsior et al., 2007)

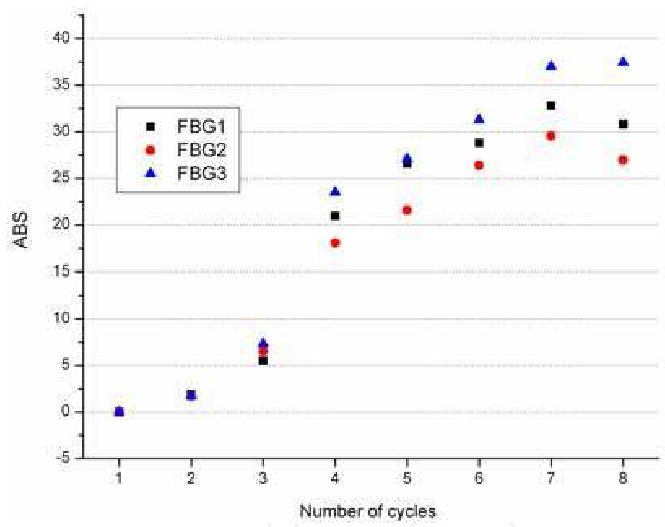


Fig. 12. Analysis of measurement results for final vessel loading cycles (detection of defects in structure of pressure vessel), (Gąsior et al., 2007)

5.3 Cyclic tests of pressure vessels with designed flaws

A major problem in the monitoring of extremely strained composite structures is the early detection and identification of defects arising in the structure of the material. The defects can be the result of material fatigue under cyclic loads (e.g. filling and emptying of the vessel) or other events, e.g. external impacts or the exceedance of the allowable stress (pressure) and working temperature.

The standards relating to the testing of pressure vessels for storing high-pressure fuels (ECE Regulation No. 110, 2008; ISO/DIS15869.3, 2008) distinguish two main types of defects: flaws and delaminations. According to the cited regulations, a vessel with a flaw should meet the requirements of, among others, the cyclic tests at room temperature for a vessel without visible flaws.

Tests of vessels with flaws are referred to in the standards as composite flaw tolerance tests. Depending on the standard, the size of a flaw can be defined as "larger than the limit for the visual inspection, specified by the vessel manufacturer" and so no smaller than:

- length 25mm x depth 1.25mm,
- length 200mm x 0.75mm depth.

The flaws are made (by cutting) in the vessel's composite shell in the direction parallel to its principal axis (Fig. 13). As already mentioned, after the flaws are made the vessel is subjected to the standard cyclic test whose result is deemed positive if the vessel does not fail (loss of airtightness or burst).

a) b)

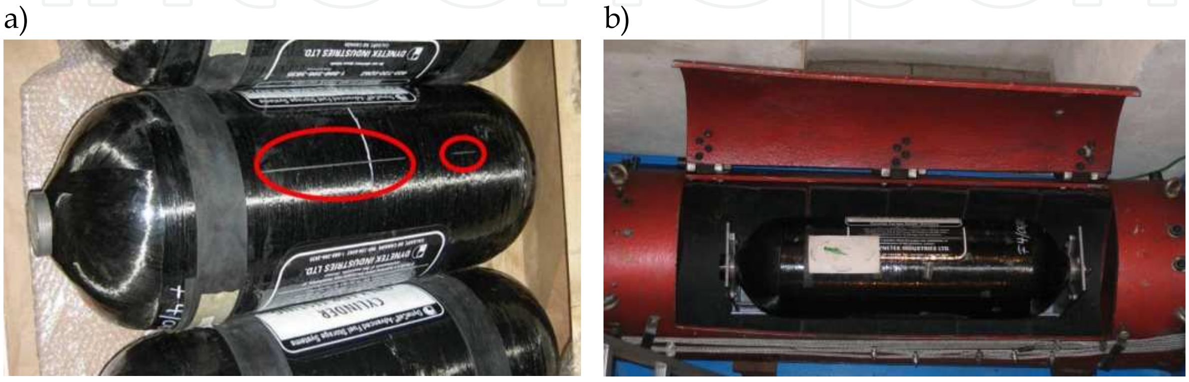


Fig. 13. Composite pressure vessels with designed flaws (cuts) (Błażejewski et al., 2008)

A pressure vessel for storing hydrogen at NWP = 207 bar (3000 psi) with 12 fibre Bragg gratings installed and two designed flaws in the form of cuts (Fig. 14) was subjected to a cyclic test at room temperature. The test consisted of over 4050 cycles in a pressure range of 20-258.5 bar (1,25 x NWP).

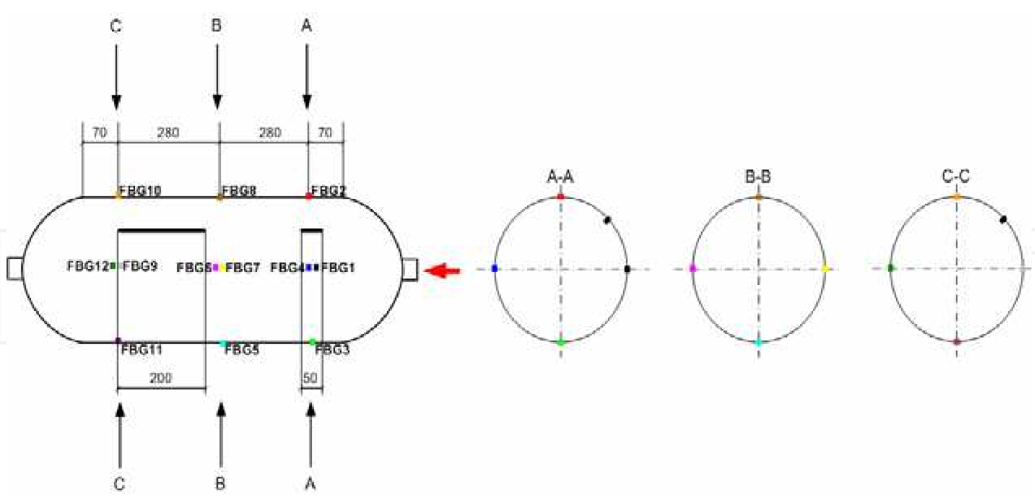
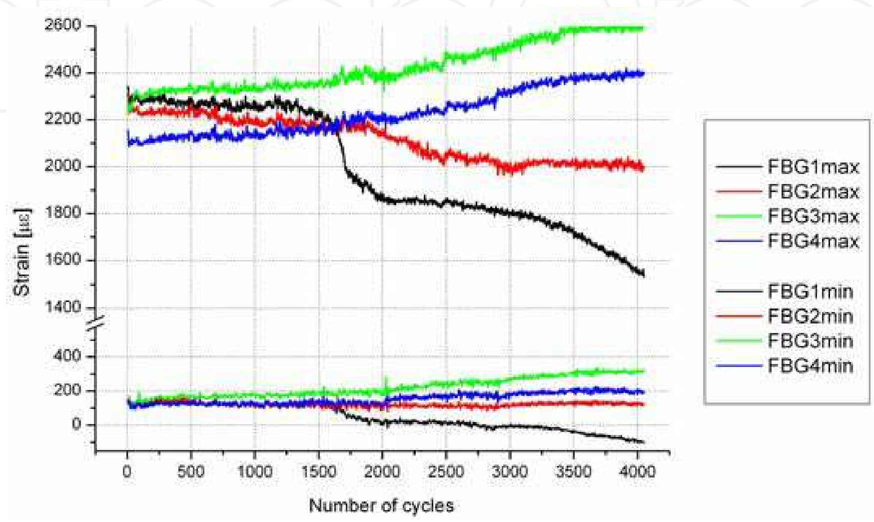


Fig. 14. Arrangement of designed flaws and sensors on tested pressure vessel (Błażejewski et al., 2008)

The measured local strains in a cross section with the shorter flaws (cross section A-A) are shown in Fig. 15. Figure 15a shows the minimum (ε_{min}) and maximum (ε_{max}) strains registered by sensors FBG1-FBG4 for pressures 20 and 285.bar. Fig. 15b shows the variation in strain amplitude ($\varepsilon_{max} - \varepsilon_{min}$) versus vessel load cycles. It should be noted that in the analyzed cross section as the number of load cycles decreases so does the strain values registered by sensors FBG1 and FBG2 located closest to the flaw. At the same time the amplitude of the strains registered by the other sensors increases. This is evidence of local defects accumulation in the load-bearing shell of the composite vessel and of the growth of the designed flaw.

a)



b)

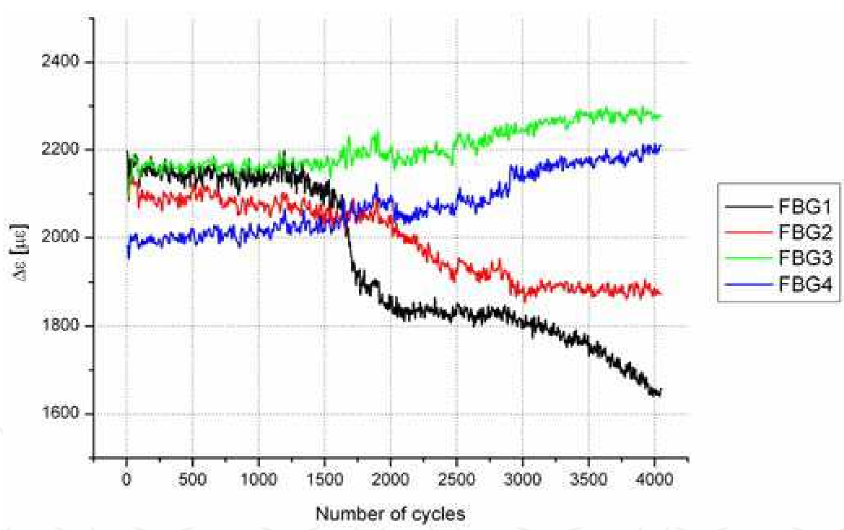


Fig. 15. Local strains of pressure vessel with designed flaws, measured by fibre Bragg gratings in cross section A-A (a) for pressure of 20 bar (min) and 258.5 bar (max), and amplitude of locally measured strains (b) versus number of vessel load (20-285.5 bar) cycles (Błażejewski et al., 2008)

The fluctuations of the maximum and minimum strain values are due to the specific character of the cyclic tests, i.e. due to the actual fluctuations of the maximum and minimum internal pressure around the fixed value (the switching pressure).

Figure 16 shows an analysis of the ABS coefficients for each of the FBG sensors installed on the tested pressure vessel, carried out in accordance with the description in sect. 5.2. It should be noted that as the number of pressure cycles increases so does the value of each of the analyzed ABS coefficients. This indicates the growth (accumulation) of defects in the tested vessel.

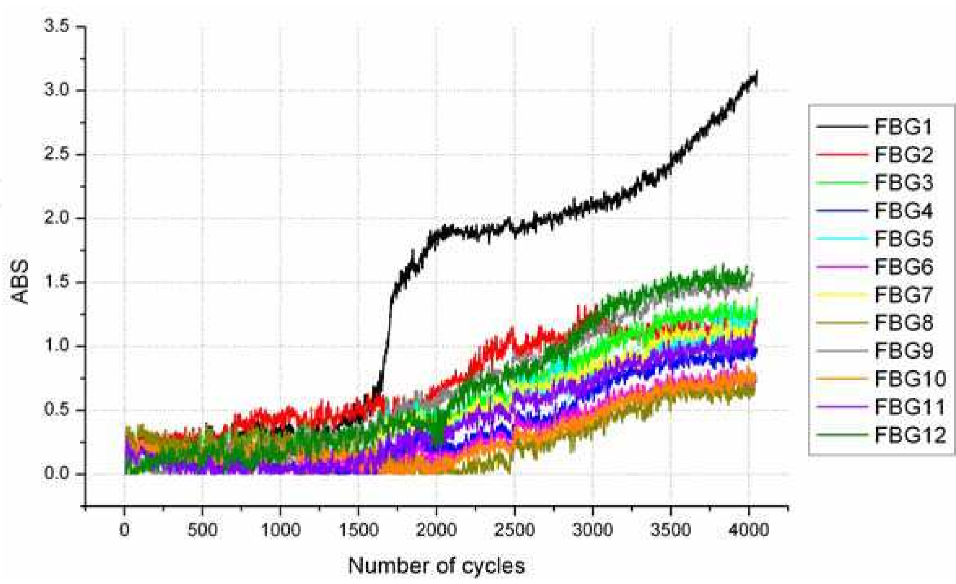


Fig. 16. Analysis of ABS coefficients versus number of pressure cycles for all FBG sensors installed on tested vessel with designed flaws (Błażejewski et al., 2008)

The largest changes were registered by sensors FBG1, FBG2, FBG11 and FBG 12, i.e. the sensors located closest to the introduced designed flaws. Moreover, one can see that the variation of the ABS coefficient, registered by sensor FBG1 after about 1600 cycles sharply increased during the next cycles. This indicates intensive local accumulation of defects, whose increase slowed down in the interval from ~2000 to ~3000 cycles, and then began to sharply increase again.

6. Conclusions

- The increasing use of polymer composites in various engineering structures necessitates the application of novel effective techniques of measuring mechanical quantities. Preferred are nondestructive techniques which would be inexpensive, reliable over the long service life of engineering structures and resistant to external influences. Measuring techniques are also expected to satisfy the requirements which structural health monitoring (SHM) systems have to meet. Systems based on optical fibre sensors (OFS) satisfy most of the requirements.
- The OFS technology offers the possibility of implementing "nervous systems" for infrastructure elements that allow health and damage assessment. Provided proper procedures are followed, optical fibre sensors can be located between the reinforcement fibres inside the composite material without affecting the mechanical properties of the composite element. Optical fibre based sensors can be used for measurements in adverse conditions (e.g. strong electromagnetic interference, high temperature and humidity) in which conventional methods cannot be used. Measuring heads based on fibre Bragg gratings have proved to be particularly suitable for composite structures. Also interferometric sensors (e.g. EFPI, SOFO®) can be used to some extent for this purpose.

- The increased interest in the novel measuring methods is also due to the many advantages of OFS over the conventional measuring methods. In practical applications measuring heads based on fibre Bragg gratings have been used most often.
- A major advantage of optical fibre sensors is that they can be used to build SHM systems comprising several thousand measuring points. This is particularly valuable when the object to be monitored is large or when it is not possible to determine the weak (critical) points in its structure. Thanks to the installation of many sensors the calculation methods can be simplified and the possibility that important information concerning the operational safety will be overlooked can be reduced. In addition, such systems are lightweight (in comparison with, e.g., strain gauge systems) and require little cabling.
- OFS can be used for on-line structural health monitoring. A major field of their application are extremely strained pressure vessels for fuel gas (methane, hydrogen). It was demonstrated that the OFS system is capable of detecting and controlling the growth of defects arising in the structure of composite materials whereby the safe service life of pressure vessels can be determined. Thanks to the way in which optical fibre sensors are installed it is possible to diagnose the health of structures during both their manufacture and long service life.
- Exemplary applications to building elements (reinforced concrete beams), composite aerospace structures and new generation of composites stimulated with a magnetic field (SGMM composites) were described.

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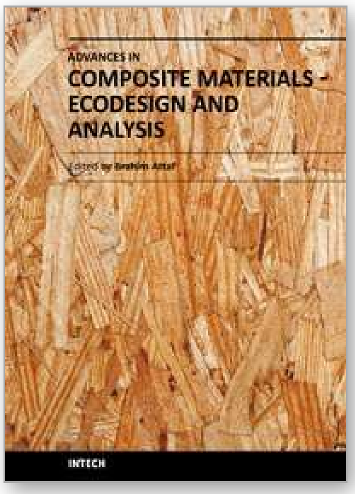

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By adopting the principles of sustainable design and cleaner production, this important book opens a new challenge in the world of composite materials and explores the achieved advancements of specialists in their respective areas of research and innovation. Contributions coming from both spaces of academia and industry were so diversified that the 28 chapters composing the book have been grouped into the following main parts: sustainable materials and ecodesign aspects, composite materials and curing processes, modelling and testing, strength of adhesive joints, characterization and thermal behaviour, all of which provides an invaluable overview of this fascinating subject area. Results achieved from theoretical, numerical and experimental investigations can help designers, manufacturers and suppliers involved with high-tech composite materials to boost competitiveness and innovation productivity.